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Eye Controlled Simulation of Scotomas on the Retina

Annual Report

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A scotoma simulation system was developed to approximate the visual losses which might be expected as an aftereffect of laser exposure. The scotomas or visual blindspots were generated using eye controlled displays which moved a masking blindspot with the subjects eye movements during visual performance tasks. These eye controlled scotoma movements eliminated the central vision in these normal subjects during the experimental sessions in the same way that retinal damage from chronic or acute laser exposure might reduce central retinal visual sensitivity. Initial data strongly suggests that training will reduce the deficits associated with central visual loss.

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Summary

A scotoma simulation system was developed to approximate the visual losses which might be expected as an aftereffect of laser exposure. The scotomas or visual blindspots were generated using eye controlled displays which moved a masking blindspot with the subjects eye movements during visual performance tasks. These eye controlled scotoma movements eliminated the central vision in these normal subjects during the experimental sessions in the same way that retinal damage from chronic or acute laser exposure might reduce central retinal visual sensitivity.

Measures of fixation stability were taken during scotoma simulation while the subjects attempted to maintain an acuity target near the fovea. The presence of a simulated scotoma caused grossly distorted eye fixation patterns when compared to normal fixation control. Abnormal patterns were reduced as subjects became more experienced with the simulated visual losses.

Visual losses due to immediate versus long term laser aftereffects were addressed in the development of both positive scotoma (afterimages) and negative scotoma simulations. The general method of scotoma simulation has value because it allows testing of the effects of the size, position and shape of scotomas in normal subjects under complete safety. Keywords: Laser damage, Focusing, [illegible] training (KW).

Foreword

For the protection of human subjects the investigator has adhered to the policies of applicable federal law 45CFR46.

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Introduction

The purpose of this project was to widen and detail the application of a simulated scotoma technique developed in the first contract. The use of this simulated scotoma method is a versatile and safe way to examine the effects on visual performance of loss of central vision due to accidental retinal injury from trauma, disease or over exposure to intense light sources.

An important advantage in using the simulated scotoma method is that the simulated injury can be accurately placed at any point on the retina in a normal human subject, either across the fovea or out in the periphery. Another advantage is that the simulated scotoma can be adjusted to produce different levels of severity of simulated injury . Finally, the simulated scotoma effects can be measured from the first presentation of the scotoma so that the subjects' adaptation to the visual loss can be monitored. In this way it is possible to simulate the conditions from just before an injury through the initial loss of vision and to follow the development of adaptation effects in the period immediately after the injury.

The simulated scotoma method can be used without risk of any kind to personnel. For example, the effects of accidental exposure to intense light, disabling some part of the retina, can be repeatedly examined without the use of any intense sources at all. A normal human observer is shown a visual display while his eye movements are measured. These measurements are then fed back into the visual display and used to alter the area which the observer is looking at. As the observer looks around the display this area of distortion or masking or scotoma follows the eye so that nothing can be seen in that area of central vision. This simulated scotoma can be varied in size, position on the retina and depth, ie. the relative insensitivity or degree of injury.

Since there is no potential for injury with a simulated or eye linked scotoma it is also possible to make simulations last for extended periods and to simulate repeated exposures without diminishing effects. The afterimage from visible light sources might produce an afterimage which lasts for a considerable period. To reproduce this effect without the eye controlled simulator would require exposing the subject to repeated

flashes of intense light. Only limited testing can be made with such intense light since repeated flashes of intense light produce adaptation effects. Also, an afterimage bright enough to produce a mask effect lasting for several minutes may be unacceptably bright.

The degree of impairment from central retinal visual loss might be quite different depending on the demands of the visual tasks. A large scotoma in the periphery might not be very noticeable if the task demands only low levels of acuity. However, even a relatively small scotoma in central or foveal vision might produce a large impairment in visual performance, especially if the task involves the use of detail vision.

Simulated central scotomas or stabilized retinal masks have been used on a very limited basis to investigate the functions of peripheral versus central retinal inputs to various visual processes. When artificial central scotomas are positioned across the fovea there is an increase in contrast sensitivity thresholds (1,2). Stabilized central scotomas have also been shown to reduce the motor component of convergence and divergence responses (3,4). During reading single lines of text, a stabilized horizontal mask slows reading rate and increases eye fixation duration (5). Recently Bertera (5) used a simulated scotoma to examine the effects of loss of central vision on visual search time, eye fixation duration and saccade length. The results showed that a 10 or 20 minarc scotoma could seriously disrupt search performance when it was in the fovea. Both search time and eye fixation duration increased significantly. However, in that study the search task was so designed that the evaluation of eccentric eye fixations was not possible. This report describes the eccentric viewing strategies during scotoma simulation since eccentric looking (moving the scotoma away from the area of visual interest) may be the principle method for countering the effects of visual loss.

Several factors are critical in producing a scotoma simulation with sufficient fidelity to be useful for interpretation of adaptive responses during eccentric viewing. Accuracy in positioning the scotoma is especially important to simulating the effects of small, centrally placed scotomata because small errors in position may allow very efficient adaptive responses to compromise interpretations. The delay between eye

movement and scotoma movement is also critical in a simulation because even small delays may supply a brief but useful glimpse of the scotoma region of the display. Finally, the ideal visual display system and display controller should be able to produce a range of contrasts among the background, foreground (test targets) and the scotoma image.

Both positive and negative scotomas or afterimages may block visual information being transmitted from retina to brain after an eye injury. In a positive afterimage scotoma the subject sees a bright spot floating with the eye movements in central vision. The afterimage from a photoflash best exemplifies this effect. A strong negative afterimage is less familiar except to some of those who have eye disease. This may take the form of a black or grey hole floating in the central area (or elsewhere) or a less visible area of distortion which makes reading or visual search very difficult.

The scotoma simulation techniques developed in the present contract have included both positive and negative scotomas. The simulated scotomas were implemented with both an analog CRT display and a raster display. The advantages and disadvantages of raster versus analog displays relative to the range of scotoma specification can be considered in terms of the scotoma delay (SD) and the scotoma image complexity (SIC).

Development of methods to reduce SD and increase SIC have been two objectives of the present study. SIC relates to both the size, complexity of shape, pattern (multiple or single) and density of the scotoma image. The SD is functionally represented in the time taken to cover, obscure, or degrade the scotoma area of the display after the eye has moved to it. A long delay between eye movement and the updating of the scotoma position makes the display imagery easily visible. Shorter delays before the scotoma onset or masking may give a glimpse of the image in the scotoma area depending on the contrast between the scotoma and display image. The ideal conditions would be to simulate an SD of zero. However, a zero delay is only possible in a case of true retinal lesion. The SD visibility effect may supply enough unmasked visual information for a correct response by itself or to facilitate a correct judgement with the addition of eccentric viewing. All eye position recording and

scotoma generation methods have delays of at least 5 msec. Fortunately, this SD is adequate to produce a good level of simulation fidelity.

The fidelity of simulation in the size, shape and pattern of the scotoma image is related although not necessarily dependent on SD. The positive circular scotoma image on an analog display has proven to be the best simulation of the SD variable. The positive scotoma is created by overlaying a CRT image (defocussed to achieve size) on a graphics image using beam splitters and its simplicity allows relatively fast movement (under 6 msec). However, this faster processing speed and lower scotoma delay is accompanied by a fixed shape and size limitations.

Larger scotomas require a different technique involving many point plotted CRT images because a single defocussed CRT spot can not be used to achieve a larger scotoma or irregular borders. The scotoma delay increases with the number of CRT points which must be used to create a larger scotoma or a non-circular small scotoma. The larger positive overlay can be implemented with a dedicated processor which plots many CRT points to form an image, but there are still time limits to the complexity of the shape Another important limitation of the positive overlay technique is that only positive afterimages can be produced in this way. Further, indistinct or a graded luminance contours in the scotoma will require more data throughput, further slowing down the system and increasing the scotoma delay variable. In this case, SD goes up with SIC.

In the prototype system (Raster1) the base screen graphic or test visual display was integrated with the scotoma image with a 16 msec delay and low luminance, low contrast images. The lower contrast and lower luminance reduced visibility enough so that the SD of 16 msec was not long enough to supply useful visual information (6). When the scotoma image is the same luminance as the background the scotoma edges are invisible except when viewing densely placed targets. When the scotoma image is either brighter or dimmer than the background there is a distinct edge between the scotoma and the background. The significance of the edge effects is elaborated in the discussion section.

Since the use of eccentric looking strategies may be a major adaptation to foveal loss caused by disease in patient populations (7,8) it seems important to measure eccentric

looking in the presence of the simulated scotomas which mimic visual loss due to other forms of retinal injury. Two tasks were designed to approach the problems of eccentric eye control and changes in eye fixation stability due to the presence of the scotoma. In a fixation control task, the observer was required to maintain fixation on a centrally placed target. Good fixation control may be considered to be a basic requirement for good performance in a search task. Holding the eye steady so that a candidate target is just outside of the scotoma area will maximize the acuity particularly for targets with fine detail.

The second task involved scanning rows of text and acuity elements for designated targets. This task was similar to those used in earlier studies where peripheral and central retinal visual processes must operate together for best efficiency. The tasks both involved sufficient space around search field elements to allow specificity in determining the degree of eccentric looking. For example, when search elements are too close together it is difficult to determine whether any one eye fixation position is a fixation on target A or an eccentric or adaptive fixation to a more distant target B. In this report data are presented for the fixation control task.

Data were collected and programs were tested with the Raster1. Raster2, currently under testing, consists of a display system with an SD of 5.7 msec and higher resolution. This is an improvement over Raster1 for both the scotoma delay and complexity variables.

Methods

Subjects.

Two of the five subjects were naive as to any of the eye movement strategies involved in eccentric viewing or adaptation after central visual loss. One was experienced in eye movement recording. All had normal vision and one wore a correction during the study. They were aged 18-45 years old and were in good health. The purposes and procedures of the study were explained and the written informed consent was obtained.

Apparatus

Horizontal and vertical analog eye position outputs from an SRI dual Purkinje tracker were used to control the X-Y scotoma coordinates. The analog outputs were low pass filtered at 100 Hz. A data acquisition computer with digital to analog and analog to digital converters recorded the eye position measurements from the eye tracker and updated the scotoma coordinates. For the CRT scotoma, updating of the scotoma position occurred every 5.5 msec, for Raster1 updating occurred every 16 msec (maximum - some updating was faster) and for Raster2 updating occurred every 5.7 msec.

The right eye was used to position the scotoma since the tracker only records from the right eye (Figure 1). Placement of the scotoma was controlled by analog outputs for X and Y and was accurate to better than 5 minarc. The subjects steadied their heads with a dental mould to insure accurate eye movement recordings. Calibration targets were used to relate eye position voltages from the Purkinje tracker to the display screen coordinates and to set the analog output levels for controlling the X-Y scotoma position.

Raster1 was the first approach to the raster graphics problem and involved a

dedicated graphic computer as a relatively low cost test of the raster method. A Sprite graphic (a hardware oriented windowing system), was fed with digitized eye positions from the data acquisition computer. This graphics system was used along with with hardware supported object movement commands. Movement commands moved a scotoma image non-destructively over a base screen graphic dependent on eye positions which were fed into a re-engineered data port. The base screen graphic contained the acuity targets, some text or a picture (Figure 2).

The Raster1 display ran at 60 Hz refresh rate and had a resolution of 320X200 pixels (4 min per pixel). The calibration of the eye position relative to voltage output from the Purkinje tracker was performed using a superimposed display screen via a beamsplitter which was aligned with the scotoma display for the scotoma and visual images.

Raster2 was the second approach to the raster simulator problem involved the construction of a system which also integrated the task visual display and scotoma display within one system (Examples are shown in Fig 6). Integrating data acquisition functions within the system may allow closer synchrony between scotoma movement and eye position sampling to yield a lower SD. The raster display was a re-engineered white phosphor raster monitor running at a frame rate of 180 Hz, three times faster than a conventional raster monitor. This produced screen changes which were as fast as the CRT display system used for scotoma simulation in previous studies.

These raster methods for scotoma generation contrast with the non-integrated display method where optical superimposition is used to place a CRT scotoma image over the base screen image While this method limits the scotoma complexity it has the advantage of providing two channels for separate manipulation of the scotoma and base screen. While some data was collected with the analog system, the main effort continues to be directed towards development of the the raster technology.

The raster technology supports specific contract objectives to enlarge the scotoma size (SOW 3.12.c), to develop a scotoma with graded edges (SOW 3.1.1), to attempt to grade visibility through the scotoma (SOW 3.1.c), to generate multiple scotoma patterns (SOW 3.1.c). The multiple scotoma patterns created the most difficult

challenge because the area of the entire scotoma is related to SD on scotoma movement. Closely spaced small scotomas with indistinct edges are the most difficult simulation to produce with current technology.

Procedure.

The observers were instructed to monitor a central acuity target so that it appeared as clear as possible. The target was a 4 minarc dot surrounded with a cross. The subjects were dark adapted for 10 min. and given some practice trials to demonstrate the targets and task. Rest breaks were given every 5 min and as needed.

The subjects were not given any specific instructions to suggest eccentric looking strategies but they knew that the only way to monitor the central target was to look slightly away to move the scotoma off of the central area. Thus they were required to use their peripheral retina to find the target and gap. A trial lasted for 15-30 sec. and an inter-trial interval of approximately 15 sec was interposed between trials.

Data Analysis.

Data were discarded if there were any large head movements or track losses. The location of blinks and track losses in the data were marked and data samples which were taken 250 msec before and after the mark were discarded. The eye position samples were stored on disk in x an y arrays along with duration readings. They were then preprocessed in preparation for analyses of dispersion, eye fixation duration, saccade length and spatial distribution (SOW 4.1.c)

The Raster1 data were transferred to an IBM AT computer via floppy disks and grid fields were created with sample counts at each grid intersection. The grid fields were mapped topographically relative to the visual target locations. The bivariate contour ellipse areas and and standard deviations for horizontal and vertical eye position sample locations were calculated to estimate the changes in the stability of fixation and the position of eccentric eye fixations. The mean position for x and y were also calculated to determine the average error from an instructed fixation point under no scotoma and scotoma conditions.

Results

Scotoma Simulator

The relative performance across the three simulator types can be compared in terms of the spatial characteristics of the scotoma and the system response or scotoma delay. The three systems all produced useful scotoma simulations but they differed in the size and shape of the scotoma which could be produced within an acceptable scotoma delay. The most advanced imagery was generated using the Raster2 system because Boolean operations could be carried out at the scotoma site.

The high speed Raster2 system was clearly the most favorable for further development when compared to the brightspot overlay method used in the earlier scotoma simulation. Variations in the scotoma shape are possible with the raster systems along with reversal of the contrast relations among the scotoma the background and the foreground. The non-integrated CRT system which generated a positive scotoma can simulate only a bright spot over the display area corresponding to the fovea. While such a positive overlay may simulate a scotoma due to an afterimage from visible light, the scotomas produced by infrared sources and long lasting or permanent scotomas may consist of distortions or holes in the visual field more similar to the raster systems.

Directionality of Eye Position Samples.

The distribution of eye position samples was asymmetrical relative to the central target in all subjects (See Figures 3, 4 and 5 for examples from three subjects). All of the observers quickly chose eccentric viewing positions to use in fixating the target. Subject 3 (continued to experiment with other locations after determining that the upper right position was "easiest" to maintain These peripheral fixation positions essentially moved the scotoma (and the fovea) off of the target so that it became visible in peripheral vision - usually in a peripheral retinal area just outside of the scotoma boundary. The distance moved approximated the scotoma radius in most cases. In some records the eye position was maintained within a scotoma radius of the central target during changes in fixation position so that an arc of eye position samples can be

seen extending around the central target (see Figure 5).

A prominent feature of these records is the dearth of eye positions which are beneath the central target. There are even fewer intentional eye fixations below the central target than appear in the topographical maps since some of those eye positions are error fixations. An error saccade from the upper right quadrant would carry the eye sometimes past the target creating a fixation point down and to the left in the visual display. The effect of an asymmetrical fixation pattern in controlling access to more complex visual information is suggested for different contexts in Figure 6.

The no scotoma or control fixation stability and mean eye position was within 5 to 10 minarc of the central acuity target on most trials (See Figure 7 D for a ten trial sample composite map) and were quite similar to the normal fixation stability found in other studies (9,10). The topographical plots of the normal fixation position showed consistency over trials with no obvious practice effects.

Open Loop Motor Errors.

There were trials in which the eye broke into a smooth pursuit mode when the observer began tracking the edge of the scotoma. This was not intentional according to the subjects reports but occurred spontaneously. Some of this behavior is represented in Figure 7 A, B and C. The upward tracks and directional patterns of the fixation samples are under further analysis. However, it is clear that sometimes the scotoma acted as a self moved target when the observer tried to fixate the edge of the scotoma. The errors represented in the upward curves are being examined further to assess the velocity characteristics of the error movements.

Measures of Dispersion

The Bivariate area, standard deviation, average angle to the target and eccentricity to the target are presented in detail for Subject 3 as an example of the analytical method. The bivariate area of the horizontal and vertical eye position samples is a measure which conveniently represents the dispersion of both the horizontal and vertical eye positions about a mean location. The bivariate area is shown in Figure 8 for ten practice periods. There is a clear decline in the bivariate area indicating that the

subject improved in maintaining a steady fixation in spite of the scotoma. The rapid nature of the adaptation is notable.

The horizontal and vertical standard deviation are also shown for S3 in Figure 9 and the same decline in dispersion of eye position samples is clearly evident. The greater deviation for horizontal than vertical eye position is typical. Why the dispersion increased for horizontal movements in the first three practice periods is not clear.

The most [illegible] position for fixation relative to the target is clearly the upper right. The average angl[illegible] [illegible] target of the mean eye position was calculated for each trial and is shown in Figure 10. The meaning of this measure is made less clear when the eye positions are dispersed, but, even in S3 where a good deal of dispersion is evident there is a notable stability in the angle to the target after practice period four (angle 100-200 is in the upper right quadrant of the visual field).

The average eccentricity from the central target is a measures which indicates how well the subject has optimized eye position. Under no scotoma conditions the eccentricity to the target should average to zero. But, with a symmetrical scotoma the subject should optimize by offsetting the scotoma by using an eccentric fixation at a distance of approximately the radius of the scotoma. Figure 11 shows that for S3 this was the case. The eccentricity is variable during practice periods 1-4 and the scotoma covered the target (eccentricities less than the radius cover the target). After the fourth period the eccentricity optimizes so that the scotoma is held away from the target with about 10 minarc between the edge of the scotoma and the target. It is also notable that this optimization of the eccentricity variable occurred at the same time as the stability in angle to the target shown in Figure 10.

The eye fixation duration generally increases when eye fixation stability increases. If the eye moves less fixation time will build up in a given fixation point. With a fixed area for the criterion of an eye fixation, more stability in the fixations results in greater eye fixation durations. The pattern of eye fixation durations in Figure 12 shows a fairly steady increase after practice period 4. The very long average fixation duration for period three is puzzling.

Discussion and Conclusions

The simulated scotoma technique was shown to produce a safe and versatile way in which to test the effects of loss of visual function from focal retinal injury. The three methods of scotoma simulation described in this report outline some of the variables which are relevant to the fidelity of simulation and the validity of the method.

The Raster1 scotoma simulator produced a scotoma delay of about 16 msec. After an eye movement which generated new X-Y coordinates there was a delay dependent on the accidental synchrony of the eye movement sampling event and the scan line position on the CRT display. This variation was between 6 msec and 16 msec. The asynchrony of the sampling period meant that there were some eye movements which were followed by brief (one video frame) glimpses of the area under the scotoma. This is not clearly visible or frequent but it does represent a limiting factor in asynchronous scotoma control which may be especially important in the inherently slower 60 Hz displays.

The Raster2 system was synchronized to the sampling system and ran at a higher rate - 180 Hz. This produced a scotoma image free from errant frames slipping through the scotoma. Also the scotoma delay was shorter - around 5 msec. These two factors together produced a higher fidelity simulation in test trials. Further work is underway to refine the 180 Hz simulator to produce very close synchrony between the video signal and the scotoma movement.

A limitation of the Raster1 method is that a relative scotoma is still technically difficult to produce. The problem in creating a transparency condition in hardware is the speed of data transfer from one position in memory to another. The overlay hardware which is currently available relies on the universal acceptance of the 60 Hz visual display standard. The transparent overlay with modulation of the transparency is the ideal condition and the outlook is positive for the transfer of developing commercial technology in the near future for this purpose. At that time the polarity of the contrast and the size of the overlay area will not restrict the simulation system performance. For the present, the restrictions on the scotoma size and transparency seem to be within acceptable limits for studying a range of problems associated with visual impairment due to central visual losses.

Another characteristic of the Raster1 system which may be important in general to all forms of scotomata is the distinctness of the edges of the scotoma. These edges were of two types: either high contrast or zero contrast. The zero contrast scotoma was an overlay which matched the background luminance and simply made the foreground imagery disappear into the background without a trace. In the background scotoma conditions the scotoma was the same luminance as the background and therefore there were only changes in the foreground characters as the scotoma moved with the eye over the visual display. In the high contrast conditions the edges were distinct and either a bright scotoma on a black background or a black hole scotoma on a lighter background.

The significance of the distinctness of the edges of the scotoma (here distinctness can be taken as both the definition and the contrast of the edges) is the visibility which is produced in peripheral vision. The more visible the edges the more information may be available to the subject of where the edge of the scotoma is in relation to a target. This may reduce the confusability of the edges with the target and ease the processing problems of finding or identifying a target in peripheral vision. The distinctiveness of the scotoma edges may also be an aid in controlling fixation stability. This stability may be a key ingredient in visual search, recognition and also detection (depending on the visual activity and structure of the background).

The higher visibility edges create a form of feedback of eye position and movement which may be an aid in countering the effects of the visual loss. Although there is not enough data on this subject yet, it seems plausible that the distinctive edges of a positive afterimage type scotoma or a black hole scotoma may aid in the production of adaptive responses. By comparison the low contrast scotoma edges are invisible until the scotoma boundary crosses a foreground target. When the target disappears within the scotoma the edge is defined. However, under conditions in which there is a low density of foreground imagery the low contrast scotoma may still be relatively invisible. This presents a serious problem in learning and perhaps maintaining an adaptation to the visual loss.

If visual conditions are present where low contrast is dominant such as winter snow, fog or haze, or other atmospheric conditions, the visual performance impairment due

to central visual loss may increase. The low contrast under such conditions is likely to conceal the visual loss from the subject and prevent adaptive processes from developing. This sort of covert loss may be detected by higher contrast test conditions if the affected retinal area is large enough. Some visual impairments may not be visible to the observer, however, until some losses are actually experienced in target detectability.

The Raster2 system embodies the characteristics of a scotoma simulator which may be useful for simulating multiple or disjointed scotomas. The speed is high enough to produce a small scotoma delay with a scotoma of useful size for study. One limitation of all of the scotoma methods used so far is that the multiple scotoma is difficult to simulate. The reason is the computation required to stabilize a large or disjointed object is intensive and this slows down the system enough to cause longer delays between eye movement and scotoma movement. However, the outlook is also optimistic for solving this class of problem since graphic controllers are now becoming available which will support multiple scotoma simulation.

One of the important study areas in the present series of experiments is the effect of the scotoma in producing motor errors in the eye movement system. The highly visible edges of the scotoma in peripheral vision may supply a strong signal for a fixation response. Under scotoma or simulated scotoma conditions this signal is also under control of the eye movements and therefore will become a self-moved target or open loop system. The eye will break into a smooth pursuit mode and slide completely out of the viewing area. This sort of error may be more serious than a momentary incompetence for fixation or an elevation in threshold since the fovea has now been driven completely out of the inspection or reading area.

It seems that the presence of even a mild positive or negative scotoma which might not produce complete block of foveal information can supply a strong signal for open loop motor errors. This can be a fairly mild positive afterimage scotoma under dark or dusk conditions, or, when a search element is tracked into an area with a darker background. Conversely, where a negative scotoma has been produced by invisible light exposure either a darker scotoma edge (produced by insensitivity of the retina) on a relatively lighter background, or, a deformed or distorted or degraded background

may supply a well defined enough signal to generate open loop motor errors.

Rapid commercial graphic chip development may allow larger displays with more resolution and a smaller SD but there are some problems in component selection and in timing purchases within the contract period. Given rapid development and price reductions, waiting for an ideal system is not as useful as a gradual development.

Phosphor speed is related to the scan rate and to visibility through the scotoma. A slow phosphor retains the displayed image and this persistent image is then still visible when a darker scotoma image is moved "on top" of it. A fast phosphor will have less persistence, and, therefore, a dark scotoma will produce greater impairments. However fast phosphors are associated with more screen flicker. Very fast phosphors are not available commercially and must be specially constructed at prohibitive cost. The fastest available phosphor is the P4 with a white display which is incorporated into the present Raster2 simulator.

The eccentricity data seem to suggest that eccentric looking strategies may develop with very little time and with no specific instruction. The rapid development and maintenance of an eccentric fixation locus found in the present studies demonstrates the high degree of plasticity in the oculomotor system. The contribution of other factors may be important as well. For example, the degree of cortical reorganization or the psychological set of the subject may be of major importance. This biological psychology factor may be used to enhance adaptation effects to central visual loss.

In the peripheral fixation task, the subjects were still able to perform even though they were given a sudden simulated loss of 2 degrees of the central retina. This is due to the simplicity of the task of holding fixation to the eccentric position. Whether performance on some tasks will be impaired by a central scotoma seems to depend on the type of task, the degree of acuity required, the contrast and the size and shape of the scotoma.

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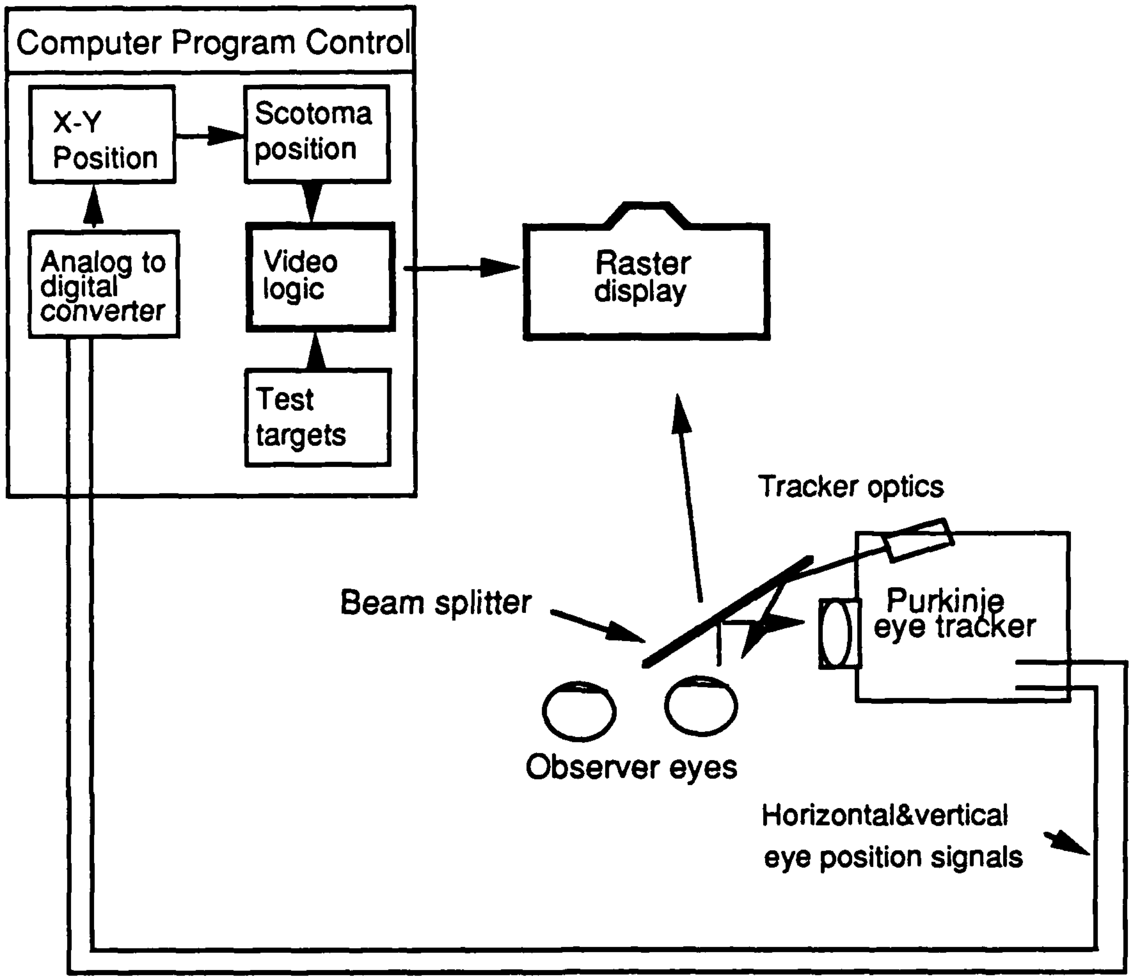

Figure 1. The scotoma simulation system is diagrammed with Purkinje Tracker, computer control elements and raster display. The subject's right eye movements are measured and the analog outputs for horizontal and vertical eye movements are fed to an analog to digital converter. Eye position relative to the raster display is then calculated from caalibration values. The scotoma movements are accurate to within 5 minarc. The scotoma and visual display are integrated together within the same raster monitor.

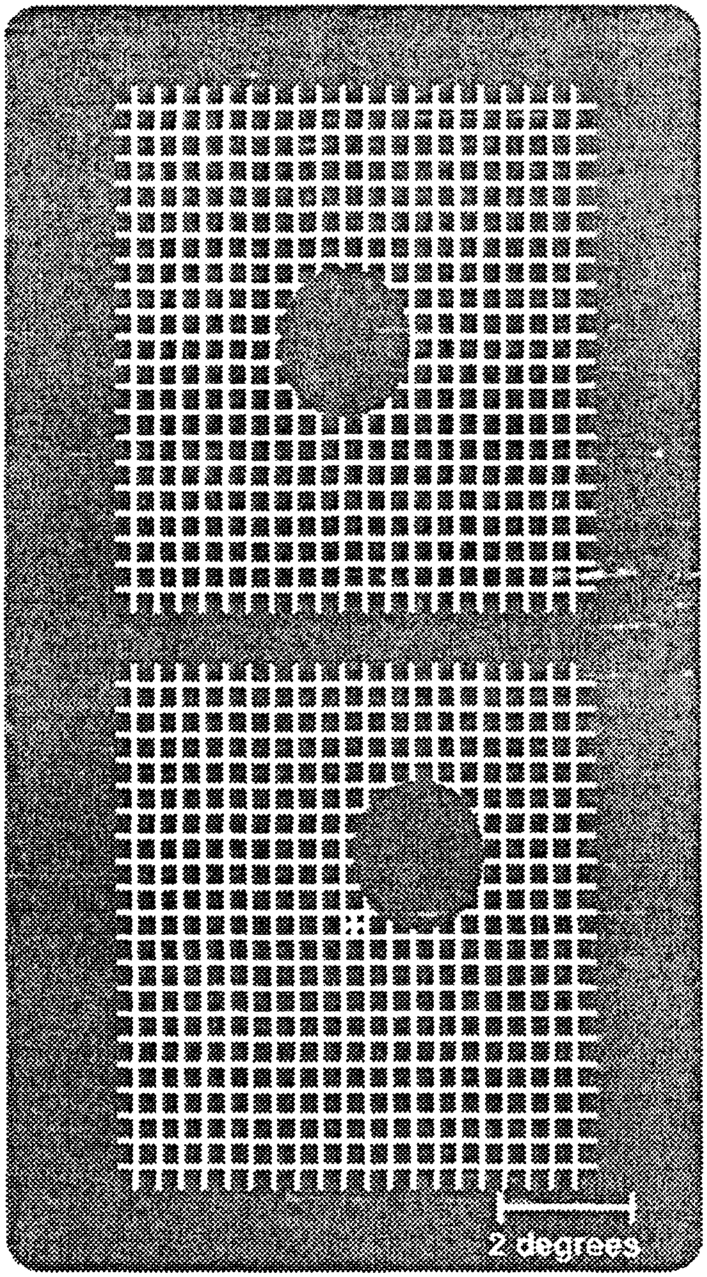

Figure 2. The central fixation target is shown with a simulated negative scotoma moving on top of a grid of white lines. The subjects attempted to keep the central white cross in view peripherally while the negative scotoma which covered the fovea moved with each eye movement. The upper panel shows the subject attempting to fixate the central target and the scotoma has obscured it. The lower panel shows the eccentric viewing position which locates the scotoma off the target making it visible in peripheral vision. The subject's fixation point and foveal center is in the center of the simulated scotoma - about 80 minarc plus from the target.

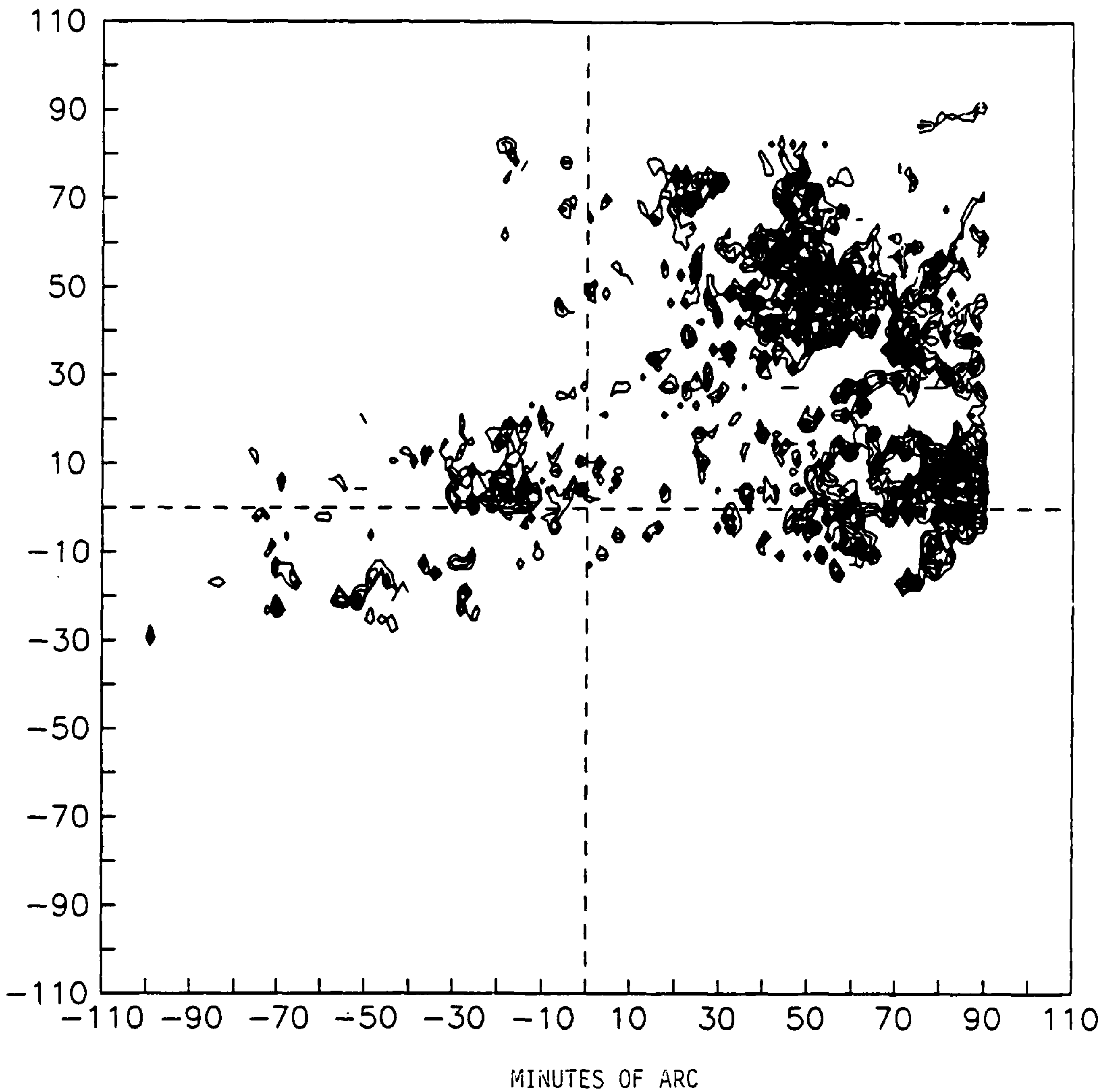

Figure 3. Composite topographical mapping of eye position samples for S1. The mapping includes about 300 sec of eccentric looking with a 2 degree scotoma across the fovea. The asymmetry obvious in the scatter of eye positions shows that the subject was fairly consistent in eccentric viewing strategy. The cluster of eye position samples near the center probably represents overshoot eye movements while erroneously fixating the target with the scotoma. The target was located at the intersection of the dashed lines. Each contour line represents 30 msec of fixation duration.

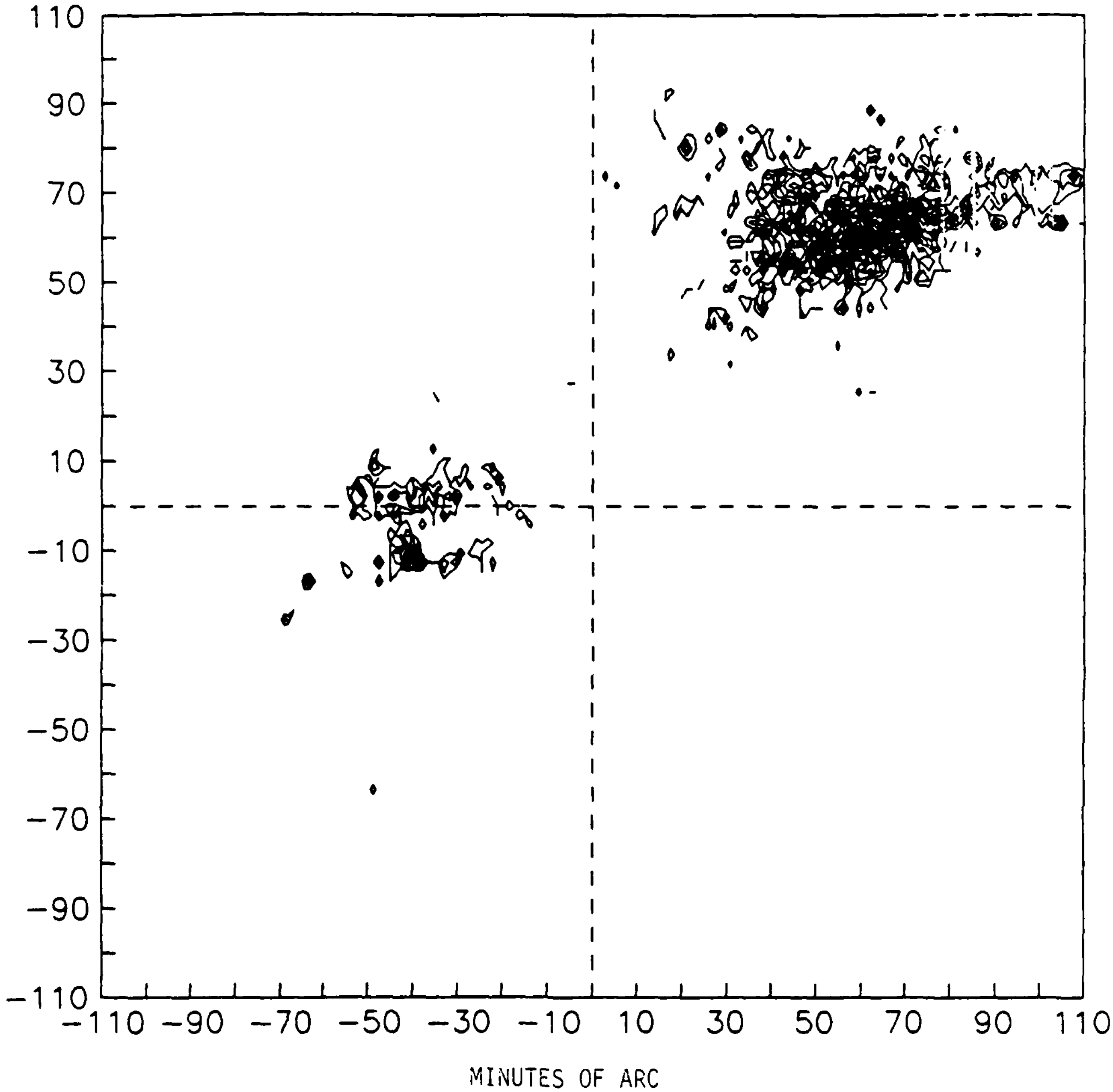

Figure 4. Composite topographical mapping of eye position samples for S2. The mapping includes about 300 sec of eccentric looking with a 2 degree scotoma across the fovea. The strong asymmetry obvious in the scatter of position samples is similar to S1. This subject maintained a more consistent eccentric fixation position. The clustering of samples near the center was due to some overshoot in refixation of the central target with the scotoma. The target was located at the intersection of the dashed lines. Each contour line represents 30 msec of fixation duration.

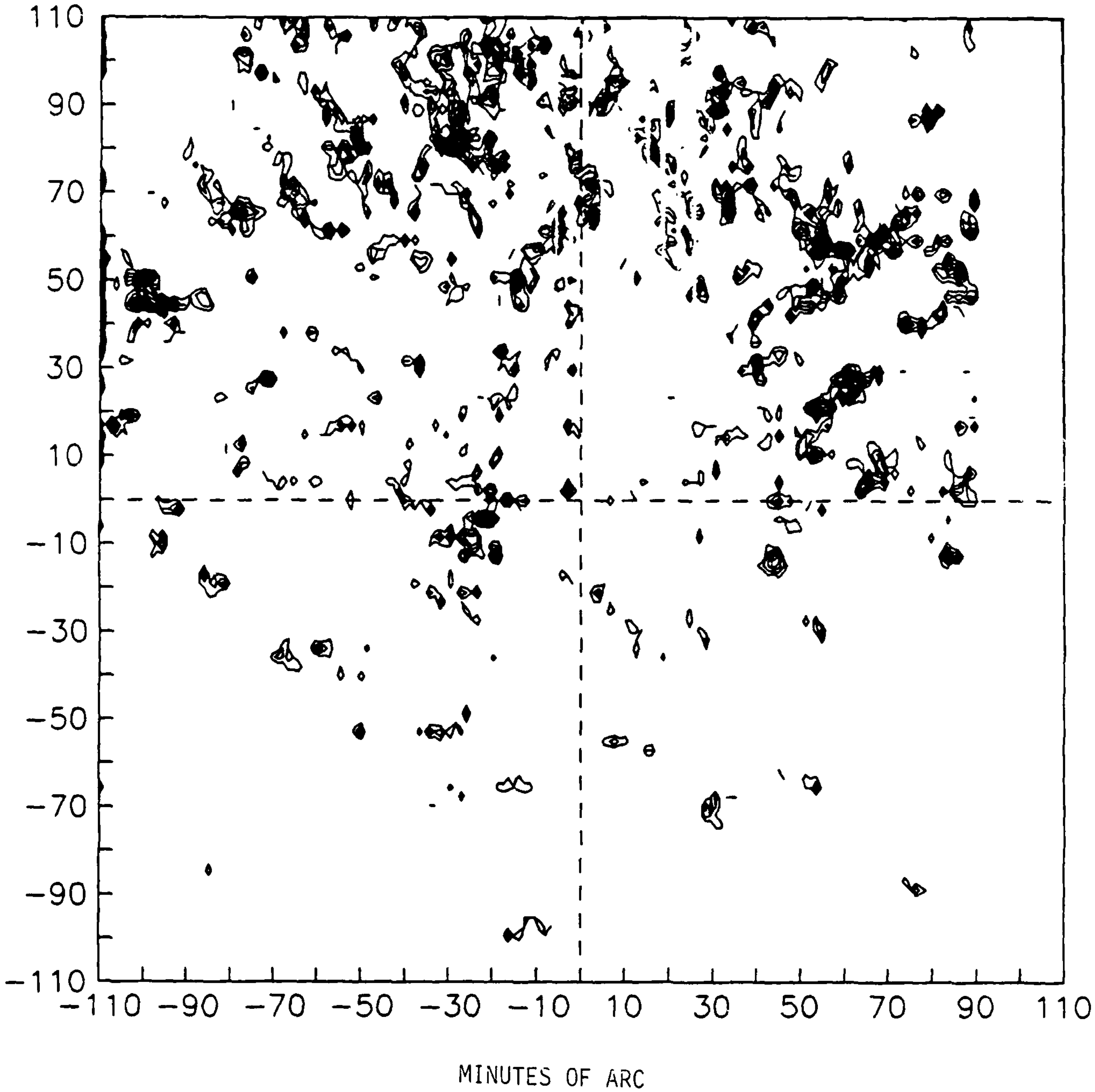

Figure 5. Composite topographical mapping of eye position samples for S3. The mapping includes about 300 sec of eccentric looking with a 2 degree scotoma across the fovea. The fixation target was located at the intersection of the dashed lines. The broad arch of samples around the central fixation target demonstrates the subject's rapidly acquired oculomotor plasticity in maintaining eccentric eye positions at various locations relative to the target. The clustering of eye position samples near the central target shows again the overshoots occurring during erroneous fixation of the target with the scotoma.

Figure 6

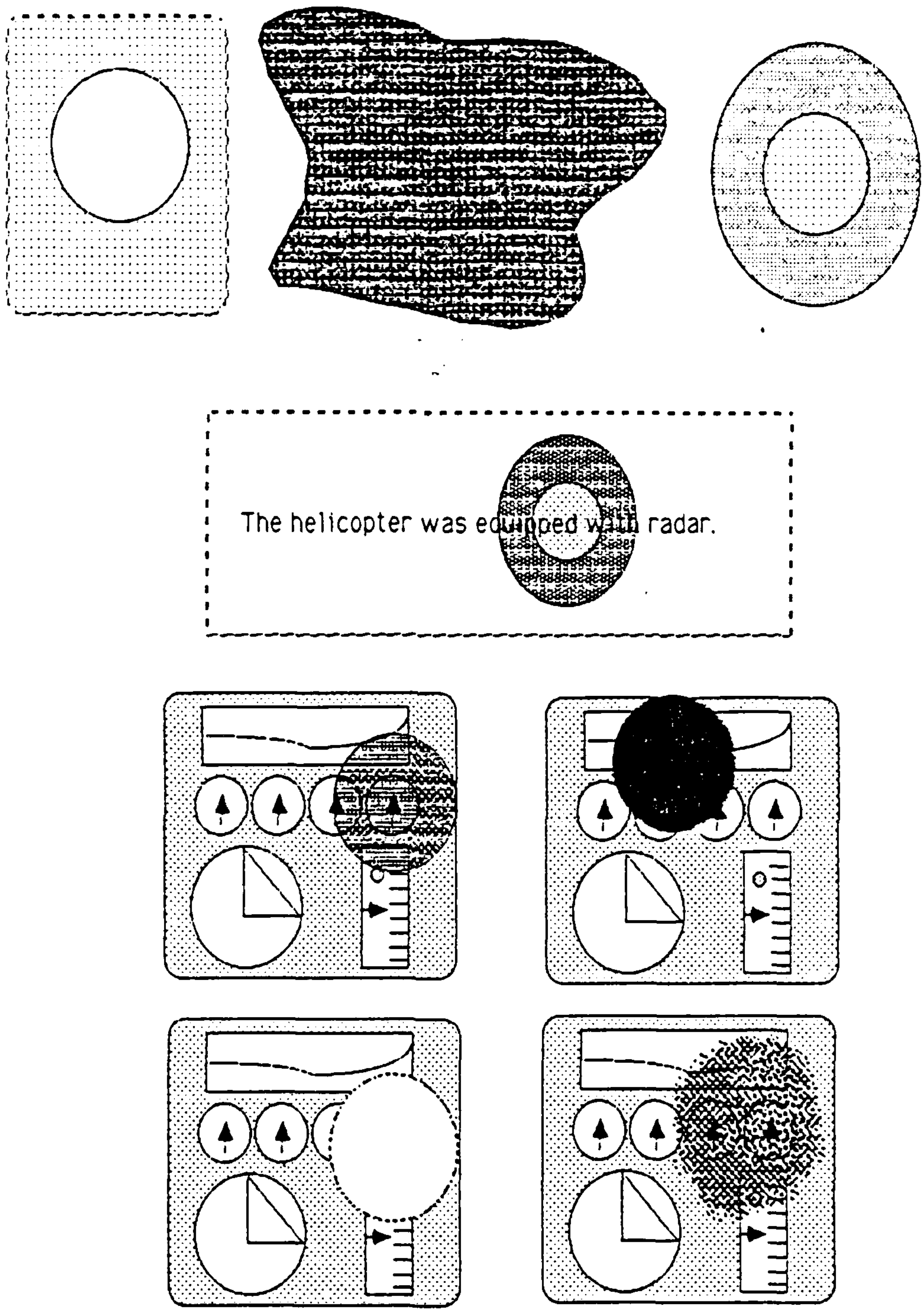

Figure 6. Examples of three scotoma types and simulated scotomas obscuring text and the visual elements of a series of instrument panels. The first scotoma simulation was implemented using a brightspot overlay on a second image (top left). The size and shape was limited along with contrast but the response speed was < 5 msec. The Raster1 system used an integrated scotoma and visual display (top middle). Although greater range was possible in size and shape response speed was three times slower. Raster2 images (top right) allow more complexity in shape, limit size somewhat, but allow transparency, contrast control and two or more levels of scotoma density with about 6 msec response latency.

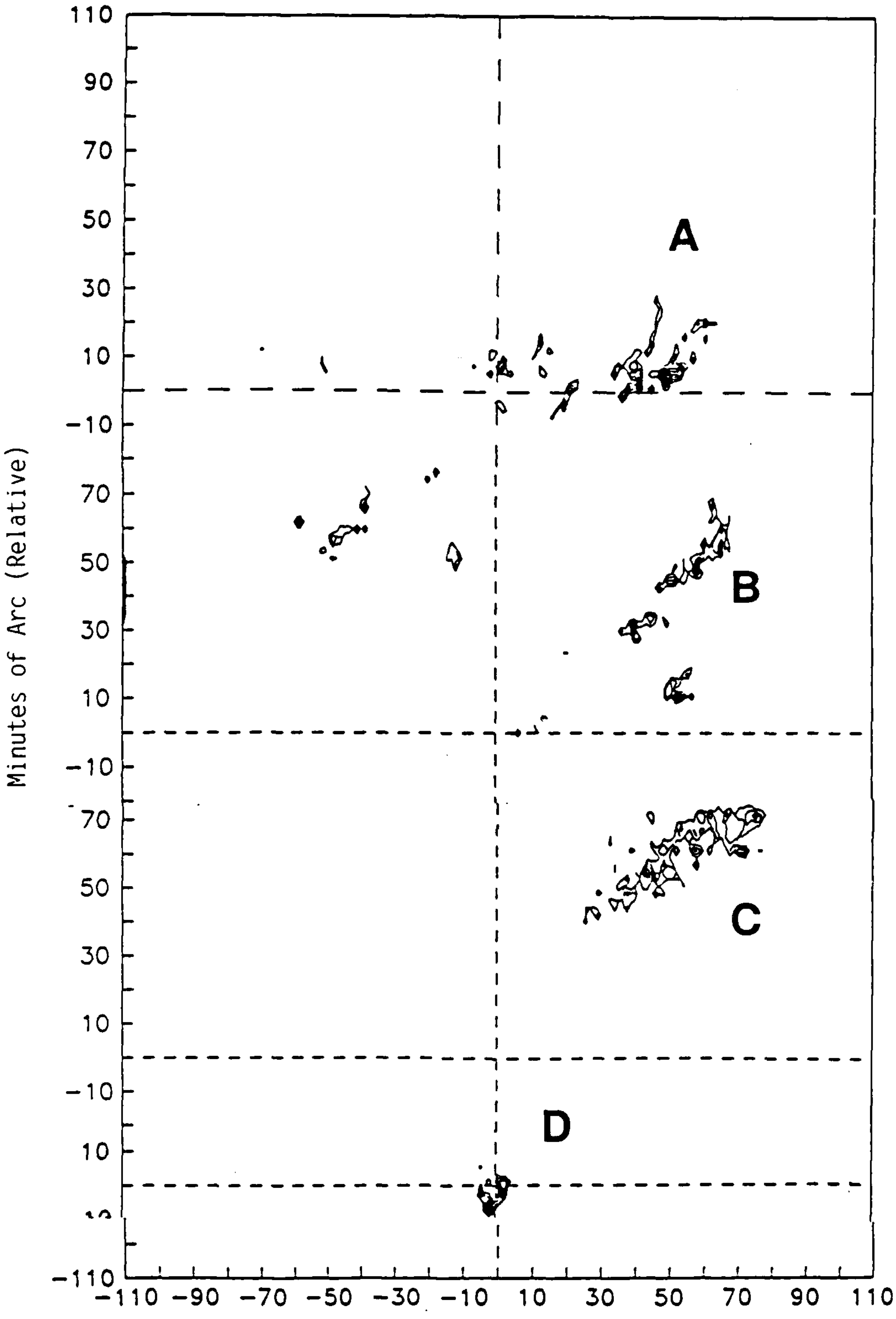

Figure 7. Directional movements with the foveal scotoma in four selected fixation periods. The bottom panel shows the normal compact and stable fixation stability pattern for eye position samples(D). The next panel shows a directional movement of the scotoma (C) along a diagonal in line with the fixation target. The next is similar - directional eye movement in line with the fixation point (B). Finally, the top panel shows directional movement but not directed to the fixation point (A). Whether these error movements are due to fixations directed to the edge of the scotoma towards the target or may be small corrections for such movements remains to be tested.

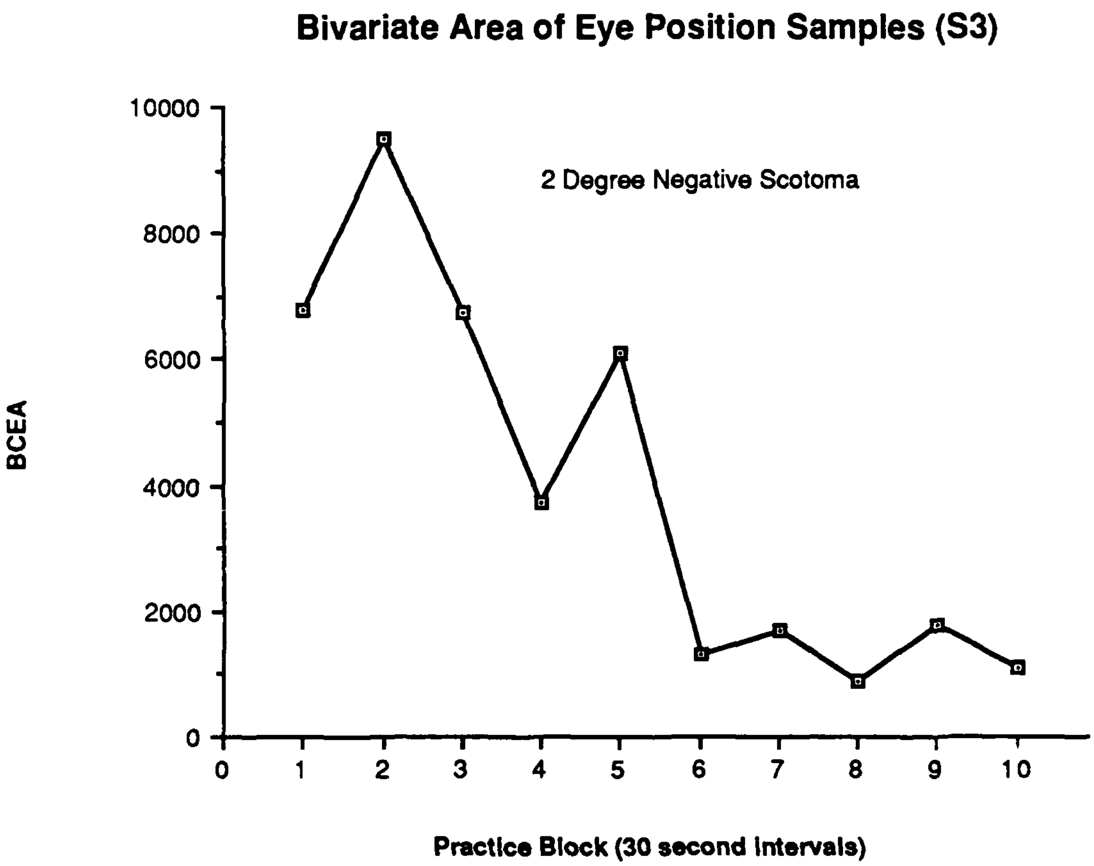

Figure 8. Bivariate area of eye position samples over 10 practice epochs. The dispersion of eye position samples for S3 generally declined to around 1000 square minarc.

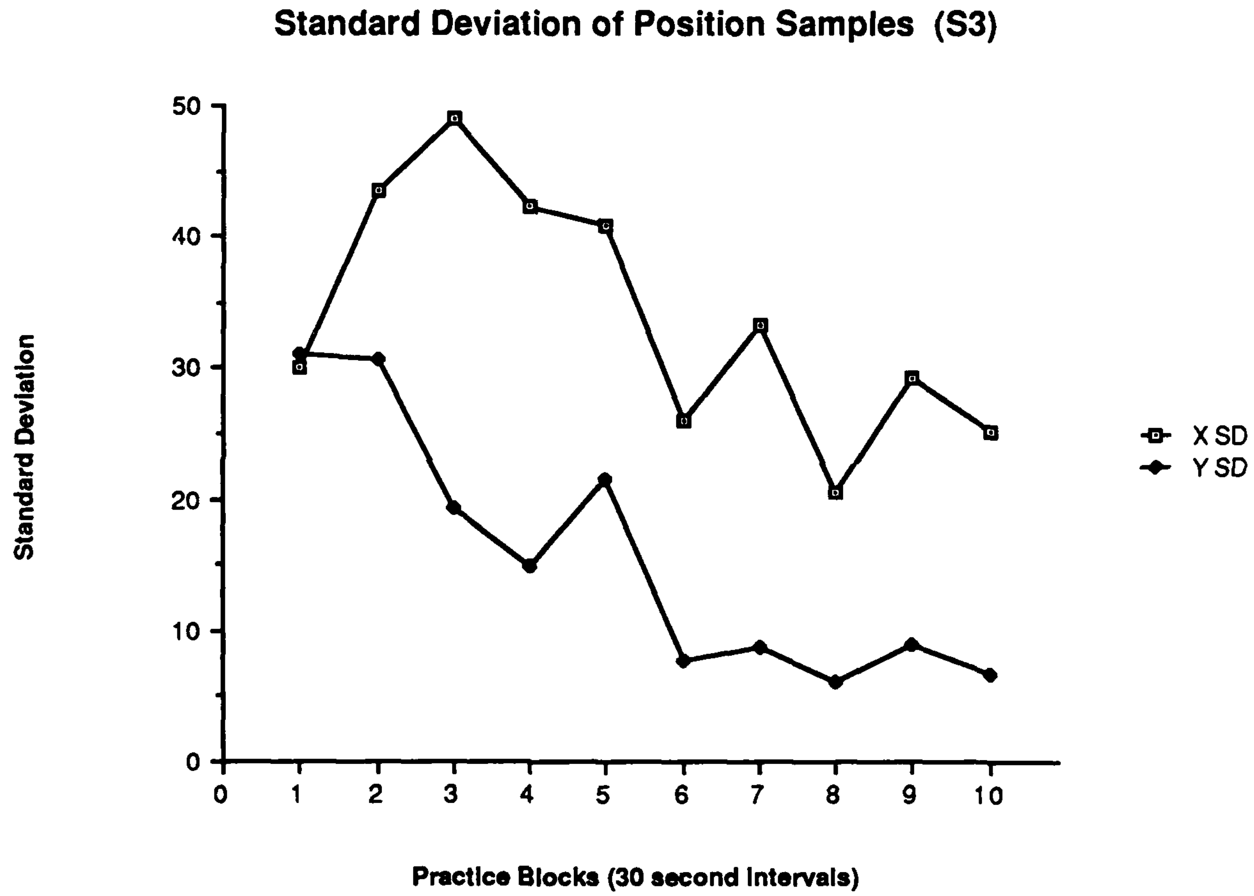

Figure 9. Standard deviations for eye position samples over 10 practice epochs. The deviations generally declined for both horizontal (X SD) and vertical (Y SD) eye position, although the dispersion increased during trials 1 and two for the horizontal eye positions. This adaptation to the simulated 2 degree scotoma shows a rapid recovery in eye control with a loss of most of the fovea.

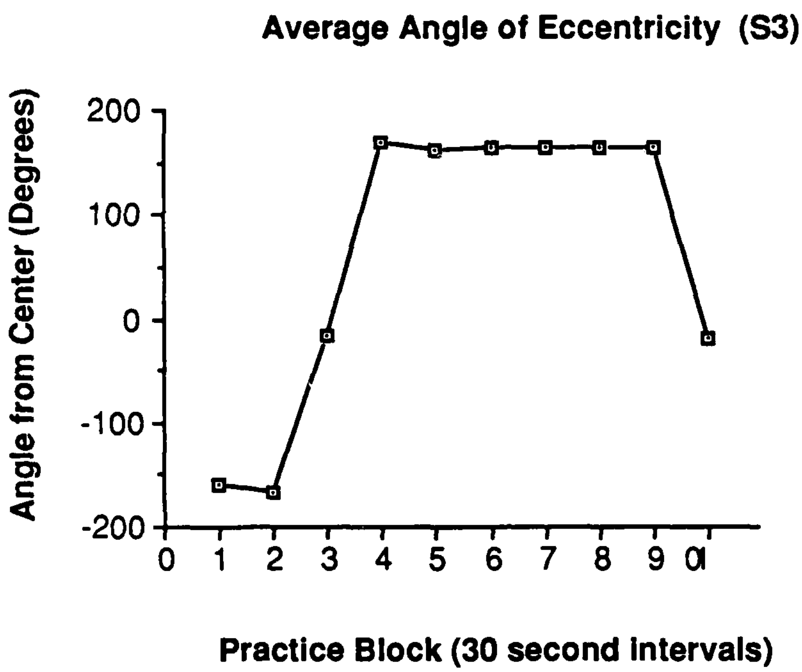

Figure 10. The angle of the mean eccentric eye position over practice epochs. This measure is dependent on the eye remaining consistently in one quadrant to be an indicator of average eccentric eye position. It is evident that the distribution of this subject's eye position samples became quite consistent at practice period 4 and remained so for 6 periods. The change in the last period was explained by the subject as testing a different strategy for eccentric looking.

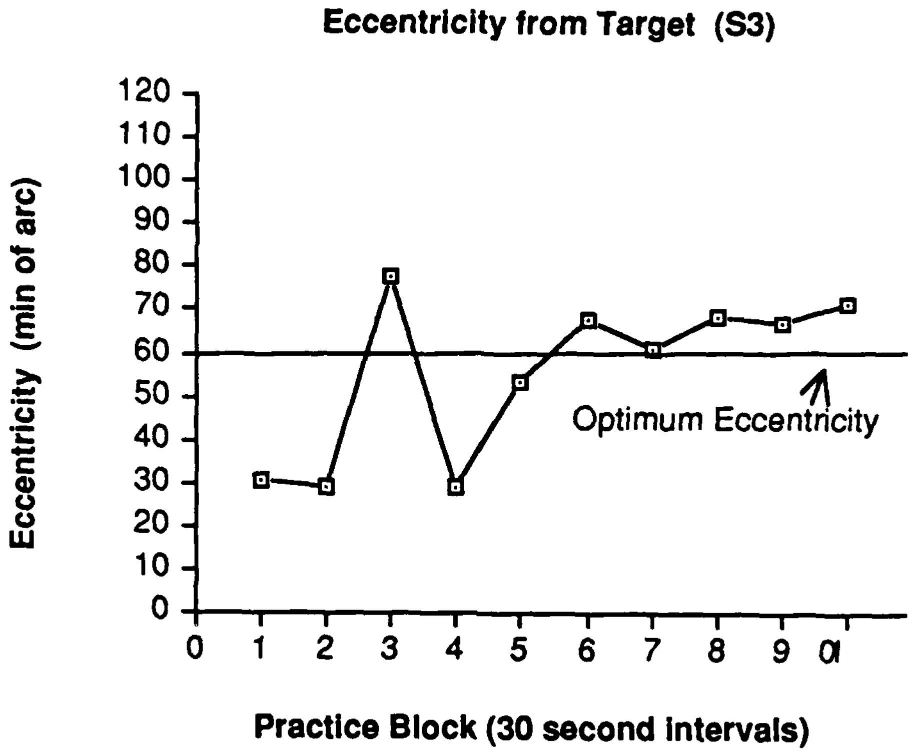

Figure 11. The average eccentricity of the eye position samples from the target center. The optimum strategy would be to maintain the symmetric scotoma at one radius off center from the target or 60 minarc. This optimum was approached within about 10 minarc. The eccentricity remaining above the optimum during the last 3 practice epochs indicates that this subject may have maintained a clear zone around the scotoma of about 10 minarc.

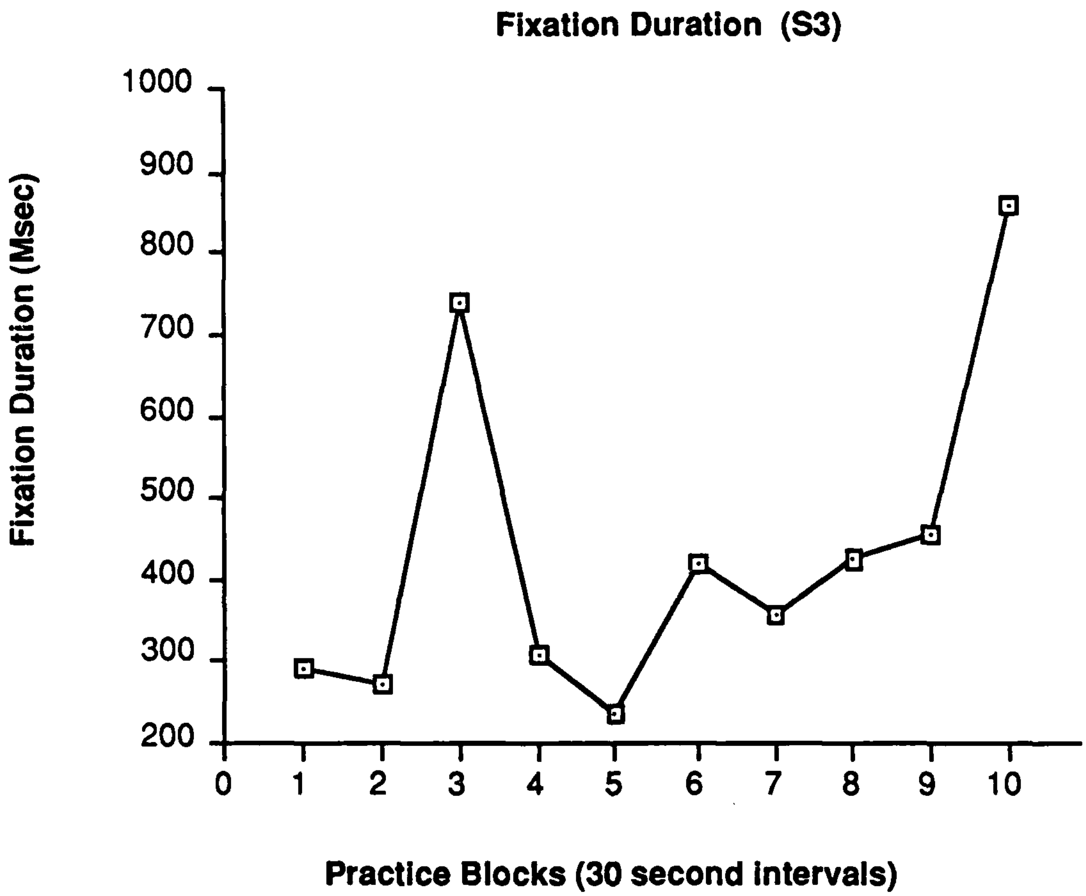

Figure 12. The average eye fixation duration over the practice epochs. The duration of the eye fixations increased from epoch 1 through 10 except for block 3. It can be seen from Figure 11 that this period was paradoxically one where performance was similar to the tenth period of practice.

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